



DEPARTMENT OF THE NAVY
NAVAL FACILITIES ENGINEERING COMMAND, MARIANAS
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IN REPLY REFER TO:
5720
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26 Apr 16

Chris Pike
University of Alaska Fairbanks
Alaska Center for Energy and Power
505 N Chandalar Drive
Fairbanks, AK 99775

Dear Mr. Pike:

SUBJECT: FREEDOM OF INFORMATION ACT (FOIA) REQUEST 16-007

This letter responds to your Freedom of Information Act (FOIA) request dated April 17, 2016, in which you seek a copy of the report compiled by Navy researchers regarding the potential geothermal resources on Guam. This office received your perfected request on April 18, 2016, and assigned to it file number 16-007.

We have located and reviewed the enclosed documents, which are responsive to your request, and they are released to you in their entirety. The cost to process your request is less than \$15.00; therefore, the fee is waived.

Further questions concerning your FOIA request should be directed to Thomas Ngiraterged at (671) 349-2277 or via e-mail at thomas.ngiraterged@fe.navy.mil.

Sincerely,

A handwritten signature in black ink, appearing to read "W. R. Lebeau", is positioned above the printed name.

W. R. LEBEAU
Commander, Civil Engineer Corps, U.S. Navy
By direction

Enclosure 1. Guam Geothermal Exploration Field Survey: Results of Phase 2 Work

Guam Geothermal Exploration Field Survey: Results of Phase 2 Work

SUMMARY

In June, 2011 Jeff Unruh and Cooper Brossy, Fugro-William Lettis and Associates, and Andy Sabin and Steve Alm, Navy Geothermal Program Office (GPO), arrived in Guam for the second phase of an ongoing geothermal exploration project. The overall objective of this project is to determine if a hydrothermal geothermal system might exist on Guam. The objective of this second phase of work included the following tasks:

- Field check possible active fault zones to determine if (a) faults previously mapped and/or identified in Fugro-William Lettis's interpretation of LiDAR data acquired over Guam were active tectonic faults, (b) what the relative ages of these faults are and (c) whether there were any indications of mineral alteration, hot fluids or steam in or near these faults.
- Field check two sites where anecdotal information suggested that steam and/or hot fluids had been identified. These sites were the Perez Bros (and others) quarry near the Hilton Hotel at Tumon Bay and Ylig Valley near the public golf course.
- Identify potential drilling targets and drilling methods to be employed if a decision to perform follow-up drilling is made
- Meet with Professor Jensen and others at Guam University to determine if any additional geothermal, geological or hydrological data exists that may assist in our exploration efforts.
- Brief CAPT Lynch, LCDR Pile, Kevin Evans and others on our progress and interim results.
- Pursue any other relevant threads of information while on the island.
- Draft a report synthesizing work accomplished to date. Conclude if follow-on work is warranted, offer costs or rough order magnitude (ROM) costs and describe this work and/or alternatives.

Based on an assessment of all relevant work previously performed on Guam, our interpretation of LiDAR and associated remote sensing data bases and results of the phase 2 field investigation, evidence for a hydrothermal geothermal system on Guam was not identified.

We also conclude that while abundant and shallow (<800 ft bgs) hydrological drilling has been performed, most wells were drilled to the north in groundwater-bearing limestone aquifers. While no anomalously hot water has ever been identified in drilling campaigns anywhere on the island¹, the most reasonable target for geothermal potential on Guam is active, tectonic faults in crystalline basement rocks. A much lower number of inventoried wells have been completed into crystalline rocks on Guam. Additionally, no heat flow data and no temperature gradient wells have ever been completed on Guam.

Given the physical isolation of Guam, the current emphasis on renewable energy alternatives and the overall lack of any previous, focused exploration for geothermal potential, a modest temperature gradient and/or core drilling/heat flow campaign on Guam with a limited number of key targets would provide more definitive insight into the geothermal potential on Guam.

¹ With the notable exception of the "hot" water well drilled by John Mink and identified in his field notes. His notes and the accompanying map identify this well in Ylig Valley. We could not find this well.

To conclusively demonstrate the potential or lack of potential for a commercial geothermal resource on Guam, we recommend a limited exploration of the subsurface via targeted drilling to document temperature gradients, especially within the volcanic basement underlying the Quaternary limestone. Specifically, we recommend targeting Quaternary faults that exhibit significant offset at sites where the volcanic basement is within reach of available drilling techniques. The motivation for targeting faults is that they may be zones of permeability that localize any potential hydrothermal upwelling. The idealized subsurface target zone for drilling would be a fault plane within the volcanic basement rocks, below the overlying limestone and the influence of flow in shallow aquifers that may dilute geothermal fluids and perturb the temperature gradient.

KEY FINDINGS

Based on our evaluation of spatial data and field reconnaissance, numerous normal faults on Guam that offset Quaternary limestone deposits were identified. In northern Guam, a variety of linear topographic escarpments with up to 20-30 meters of relief locally coincide with mapped faults or brecciated zones (Siegrist and Reagan, 2008). Many of these lineaments have greater extent than shown on published maps. Analysis of relief on the surface of the volcanic rocks underlying the limestone deposits suggests that surface faulting is linked to structures that extend into the Tertiary volcanic basement and exhibit evidence for pre-late Quaternary activity. In southern Guam, numerous faults have been mapped in Tertiary rocks by previous workers (Tracey et al., 1964; Reagan and Meijer, 1984; Kilmer et al., 2003; Siegrist and Reagan, 2008), but our investigations did not conclusively identify any evidence for Quaternary activity. Based on available information, two end-member mechanisms are possible to account for Quaternary faulting on Guam: (1) the faults are accommodating active north-south tectonic extension of the southern Mariana islands related to distributed plate motion and the curvature of the plate boundary (Heeszel et al., 2008); or (2) the faults are the surface expression of deep-seated landsliding and non-tectonic gravitational collapse of the Tertiary volcanic edifice that underlies the island.

LIDAR ANALYSIS AND FIELD RECONNAISSANCE

Analytical Approach

We analyzed high-resolution, LiDAR-derived topographic data to identify potential fault-related features and landforms indicative of Quaternary deformation on the island of Guam. Our approach included evaluating the geomorphology of the island to identify lineaments such as linear slope breaks, faceted hillslopes and linear range fronts, deflected streams, aligned saddles, and linear valleys. We also evaluated the presence of features commonly associated with active faulting such as vegetation lineaments, distinct changes in stream channel planform, and warped or deformed fluvial landforms such as stream terraces.

In order to visualize Guam's geomorphology in detail, we created DEMs with a 1-m cell size from the original LiDAR point data. The resulting DEMs were then used to create a variety of hillshade, slope (i.e., first derivative), and slope of slope (i.e., second derivative) maps. DEMs symbolized with color elevation ramps facilitated easy visualization of the elevation values across the island. Along with the high-resolution satellite imagery, these data were all imported into GIS, and through various layering arrangements and levels of transparency, provided

accurate and intuitive visualizations of the island's landforms. For example, the dramatic relief of the rugged and highly dissected southern portion of the island is readily apparent when a semi-transparent elevation color ramp is overlaid upon a hillshade base. The subtle topographic features of the largely planar epi-karst terrain in northern Guam are rendered very effectively by this presentation of the topographic data. Additional features are highlighted in this lower-relief setting when the hillshade is replaced by a slope map base. Furthermore, in areas of high relief, where the hillshade effect naturally generates shadows that obscure portions of steep slopes, a slope map illuminates more of the sloping surfaces, facilitating more thorough analysis of landforms.

Field reconnaissance of the most promising, readily accessible and potentially Quaternary-active faults and fault-related features identified in the desktop study occurred in early June, 2011. In addition to standard field equipment, a hardened GIS- and GPS-enabled laptop computer provided accurate real-time position information and facilitated mapping while in the field. The geospatial data, especially the LiDAR-derived elevation data, high resolution satellite imagery, and land ownership data, proved invaluable in navigating the island's rugged and highly vegetated terrain and evaluating potentially active tectonic features.

DISCUSSION

Based on the geothermal exploration screening protocol outlined by ITSI (2005) and Walker et al. (2005), Guam potentially exhibits several characteristics of "district-scale" prospective regions:

- 1 Guam is adjacent to an extensional back-arc region associated with the obliquely convergent Pacific-Philippine plate boundary;
- 2 Young submarine volcanic cones are present 20-30 km west of the island; and
- 3 Quaternary-active faults are present on the island, and in one case (the Perez Brothers Quarry) are spatially associated with anecdotal accounts of steam issuing from the ground.

In detail, however, evidence for an electrical-grade geothermal resource on Guam is equivocal to poor. Key criteria for prospect identification outlined in ITSI (2005) include proximity to Quaternary volcanic activity (5 km or less), the presence of active tectonic faults and relatively high strain rates, and surface manifestations of geothermal activity. Guam is not within 5 km of any known active volcanic centers, and as discussed in detail below, Quaternary faults on the island are characterized by low slip rates and probably are not accommodating tectonic deformation associated with distributed plate motion along the southern Marianas arc. Aside from the unverified anecdotal accounts of a steam vent in the Perez Brothers Quarry, there is no documented evidence of young geothermal activity on the island.

Given the absence of evidence for proximal active volcanism or a shallow source of heat, a key issue for geothermal evaluation of Guam is the activity of faults that deform the late Cenozoic limestone plateau on the northern end of the island. According to the exploration protocol of ITSI (2005), an area may be prospective for electrical-grade geothermal resources if it is subject to relatively high extensional tectonic strain rates (i.e., 10^{-15} /s or higher) and active faults are present with slip rates on the order of 0.1 mm/yr or higher, even in the absence of proximal

Quaternary volcanic centers. Thus the tectonic role and activity rates of the Quaternary faults in the northern part of the island are relevant to assessing them as prospective features.

Based on available information, two end-member mechanisms are possible to account for observed Quaternary faulting on Guam:

- 1 The faults are accommodating distributed tectonic deformation in the southern forearc region of the Marianas subduction zone (Heeszel et al., 2008);
- 2 The faults are the surface expression of deep-seated landsliding and non-tectonic gravitational collapse of the Tertiary volcanic edifice that underlies the island.

In support of the tectonic hypothesis, geodetic and seismotectonic data suggest that the southern part of the Marianas forearc region may be accommodating regional north-south tectonic extension. Heeszel et al. (2008) summarize available GPS data indicating that Saipan and Guam are moving away from each other at a rate of 5 mm/yr. Averaged over the approximately 200 km distance between the two islands, this rate of separation implies an average extensional strain rate of about 8×10^{-16} /s along the trend of the Marianas arc, which is slightly less than the 10^{-15} /s strain rate cited by ITSI (2005) as a critical threshold for “district-scale” prospective regions. It is important to note that this geodetic deformation, if accurately derived, may be occurring anywhere *between* Guam and Saipan, and not necessarily including Guam itself. Heeszel et al. (2008) also reviewed seismicity data from the Marianas chain and reported that focal mechanisms of earthquakes from a swarm near the island of Rota less than 100 km north of Guam indicate normal faulting along east-west striking nodal planes. They note that the events are “located on or very near a diffuse east-west-trending line of small volcanic seamounts running perpendicular to the volcanic arc, suggesting north-south extension is occurring in this region. The kinematics of the seismogenic deformation are consistent with north-south separation of Guam and Saipan observed in the GPS data. In the current seismotectonic setting, therefore, Quaternary normal faults on Guam may be accommodating a component of distributed plate motion.

In detail, however, the style and rate of faulting on northern Guam do not fit this regional tectonic model. The radial pattern of faults about Mt. Santa Rosa does not obviously accommodate uniform north-south extension consistent with the GPS geodesy and seismotectonic data (Heeszel et al., 2008). The magnitude of normal displacement on the faults appears to systematically increase with radial distance from Mt. Santa Rosa. This pattern of faulting implies fan-like opening or spreading of the crust west of Mt. Santa Rosa, and is very anomalous compared to normal faulting in regions of active tectonic extension such as the western United States.

In addition, the activity rates of the Quaternary faults on the northern part of Guam are extremely low and not consistent with the geodetic strain rates reported by Heeszel et al. (2008). For example, the vertical separation of the limestone surface across fault A1 in the northern part of Anderson AFB is about 25 m, measured from topographic profile 39. Averaged over the 2 million year age of the limestone (J. Jenson, personal communication, 2011), the implied long-term average separation rate is about 0.01 mm/yr. A similar estimate can be made for the Yigo reach of the Tamuning-Yigo fault zone. Based on a scarp height of about 45 m measured across topographic profile 16, the long-term average separation rate on the fault at

this site is about 0.02 mm/yr. If the regional tectonic strain rate of 8×10^{-16} /s implied by the geodetic data includes Guam, then the implied rate of north-south extension across the 25-km-long northern part of the island is about 0.6 mm/yr. It would require approximately 30 to 60 faults distributed across northern Guam with scarp heights similar to those of fault A1 and the Tumuning-Yigo fault to accommodate active deformation at the prevailing strain rate. Although there are numerous faults and lineaments on northern Guam, the A1 fault and Tumuning-Yigo fault have exceptionally large scarps and are not representative of much lower separation rates on most other structures. Thus, we conclude that faulting rates on northern Guam are not consistent with accommodating the geodetic strain rates between Guam and Saipan (Heeszel et al., 2008).

The low fault separation rates observed on Guam (low hundredths of mm/yr) are at least one order of magnitude lower than slip rates on faults in areas of high strain rate (slip rates of 0.1 to 1.0 mm/yr; strain rates of 10^{-15} /s or higher) in the western United States typically associated with electrical-grade geothermal resources (ITSI, 2005). It is unlikely that the low rates of fault activity on Guam, if tectonic, are sufficient to create structural conditions leading to elevated heat flow and permeability at depth similar to typical Basin-and-Range electrical-grade resources.

As an alternative to the tectonic hypothesis, Quaternary faulting on Guam may be accommodating slow gravitational collapse of the Tertiary volcanic edifice that comprises the bedrock of the island. Early work by Tracey et al. (1964) proposed the current morphology of the island resulted from the collapse of much larger volcanic edifices located to the west. Subsequent study has generated a large body of literature on the collapse of volcanic islands (e.g. Holcomb and Searle, 1991; Mitchell, 2003; etc.), including modeling of potential mechanisms of landsliding and gravitational spreading (Oehler et al., 2005).

The scale and expression of the locally curvilinear and scalloped faults on the northern part of the island are more consistent with landforms such as the headscarps of large landslides or curving paleoshorelines modified by erosion (mechanism 2), rather than seismogenic normal faults. For instance, about 2 km west of Mataguac Hill the relaxed slope angles and undulating margins of the highest portion of the plateau could be related to the original processes of formation of the limestone where the interaction of reef growth, beach processes, and subsidence from gravitational collapse combined to create distinctly non-linear slope breaks. Another possibility relates both mechanisms 1 and 2: karst weathering or other surface processes (beach erosion) locally modify both simple and complex fault scarps, resulting in variable expression along the topographic lineament. This may explain the scalloped nature of the Yigo reach of the Tumuning-Yigo fault zone.

In the case of either mechanism 1 or 2, pre-existing structures within the volcanic basement rocks may control the development of faults in the overlying Mariana and Barrigada limestone of northern Guam. For example, a structure map on the surface of the non-carbonate basement rocks beneath the limestone shows a strong general correlation between fault zones and topographic lineaments in the surficial limestones and the relief of the underlying non-carbonate basement rocks. Significant relief in the basement rocks (up to 140 m) corresponds with the trace of the lineaments of the Tumuning-Yigo fault zone, the apparent graben of the Hagatna Swamp, and a variety of lineaments around Mount Santa Rosa. Along the Tumuning-Yigo fault zone, relief on the basement rocks across the lineaments (approximately 100-140 m) is locally

greater than the relief in the surficial limestones (approximately 30-60 m). Unfortunately, the subsurface data is very generalized compared to the detail presented in the LiDAR data, and these values are approximate. Nonetheless, this relief suggests that tectonic activity began prior to deposition of the limestone in the Pliocene and continued into at least the Pleistocene when formation of the limestone ceased. A conceptual diagram of the evolution of the northern Guam limestone aquifer produced by the Water and Environmental Research Institute of University of Guam (WERI) illustrates this prolonged period of faulting. In addition, an isopach map of the estimated thickness of the limestone on the northern plateau, calculated by subtracting the elevation of the volcanic basement rocks from the LiDAR-derived ground surface elevation, also demonstrates how the thickness of the limestone locally corresponds to fault zones.

Given the very low long-term-average separation rates on the faults, we prefer the gravitational collapse model to account for Quaternary faulting on Guam. Given the evidence for activity and growth of the faults during deposition of the Quaternary limestones, they may be old Tertiary structures that date back to the main phase of large-scale collapse of the original volcanic edifice, and which have been re-activated or continuously active at a low rate in late Cenozoic time. Quaternary epeirogenic uplift of Guam, as documented by Dickinson (2000), may have slightly increased the gravitational potential energy of the island, reactivating some of the old collapse structures. Also, it is possible that the observed Quaternary activity can be explained by triggered slip due to strong ground shaking during large earthquakes like the 1993 Mw 7.7 event. As noted previously, we heard an anecdotal account from workers at the Perez Brothers Route 16 quarry that about 2 in (5 cm) of aseismic triggered slip occurred locally on the fault exposed in the quarry during the 1993 earthquake. If such earthquakes occur every 2500 years and produce similar amounts of triggered movement each time, then the apparent slip rate would be about 0.02 mm/yr, which is similar to the observed long-term-average separation rate on the fault.

To summarize, the potential for an electrical-grade resource on Guam is very low. There is no evidence for young volcanism on or directly adjacent to the island that could produce elevated temperatures and heat flow. The observed rates of Quaternary faulting on Guam are lower than slip rates associated with electrical grade resources in the western United States, and the faulting likely accommodates gravitational settling of the island rather than distributed tectonic plate motion.

RECOMMENDATIONS

To conclusively demonstrate the potential or lack of potential for a commercial geothermal resource on Guam, we recommend a limited exploration of the subsurface via targeted drilling to document temperature gradients, especially within the volcanic basement underlying the Quaternary limestone. Specifically, we recommend targeting Quaternary faults that exhibit significant offset at sites where the volcanic basement is within reach of available drilling techniques. The motivation for targeting faults is that they may be zones of permeability that localize any potential hydrothermal upwelling. The idealized subsurface target zone for drilling would be a fault plane within the volcanic basement rocks, below the overlying limestone and the influence of flow in shallow aquifers that may dilute geothermal fluids and perturb the temperature gradient.

In order of descending rank, recommended locations include: (1) Fault A1 on Anderson AFB; (2) the Tammuning-Yigo fault zone; (3) the Perez brothers' quarry near the Hilton hotel west of Tumon Bay (where steam vents purportedly once existed). Sites within the naval magazine also should be considered because of the magazine's location along the trend of the Talofoto fault zone, but given a low priority due to the lack of evidence for Quaternary faulting. These sites are described in greater detail as follows.

Fault A1 on Anderson AFB exhibits several characteristics that make it attractive to further study. Not only is the feature of great length (12-15 km), but it exhibits considerable topographic relief, and locally consists of several strands as shown by the multiple northeast-facing topographic escarpments where the fuel pipeline crosses the scarp. Because the depth to volcanic basement along Fault A1 increases northward, drilling sites closer to Mt Santa Rosa will likely encounter thinner deposits of limestone. Several wells near the gas pipeline route and the landfill help constrain the limestone thickness and may help in choosing a specific drilling location. For example, in the area of well B-10, the limestone could be as thick as 210 m. With a constant fault dip of 65°, the fault plane will be 21 m deeper for every 10 m of distance from the surface trace of the fault in the direction of dip. In this case, the fault plane would intersect the well B-10 at ~170 m below ground surface, well within the limestone. In order to intercept the fault zone where the fault lies within the volcanic basement, the drilling location will need to step out a horizontal distance of at least ~100 m from the surface trace. At 150 m horizontally from the surface trace, the fault is predicted to be ~320 m below ground surface and ~90 m into the volcanic rocks. Construction of scaled 1:1 site-specific cross-sections in advance of drilling is strongly recommended to test various fault geometry and basement-limestone contact scenarios.

The entire Yigo reach of the Tammuning-Yigo fault zone also is worth considering as a potential drilling target for similar reasons as fault A1. For example, the faults exposed in the quarries along the fault zone demonstrate that north-down displacement has occurred across a relatively wide zone, possible up to 10s of meters across. In addition, the surface elevation of the volcanic basement rocks adjacent to the fault is well constrained by a large number of wells. Although we were not able to visit the reach of the fault zone running through the Anderson AFB south property, the area may be a prospective drilling target because the limestone may only be 150 m thick or less assuming that the fault dip here is similar to that elsewhere along the fault zone (65-70°). As described above for Fault A1, the local thickness of the limestone and possible range of fault dips should be considered during selection of a specific drilling location.

The presence of steam vents in the Perez brother's quarry in Tumon was not verified during our reconnaissance, but airborne thermal imaging equipment such as that used by law enforcement or wildland fire fighting agencies might be able to locate subtle differences in temperature that are otherwise unnoticeable given the current ground conditions. In addition, local groundwater conditions around the quarry may have changed over the life of the quarry, such that the conditions that allowed for steam to reach the surface may no longer be present. If this is the case, then only subsurface exploration (such as drilling) would likely provide the data needed to conclusively prove or disprove the presence of hot fluids underneath the quarry. Unfortunately the quarry is located in an area relatively devoid of data on the depth to volcanic basement and the limestone thicknesses could approach 300 m or more, in which case the basement may be beyond the reach of on-island drill rigs. Consequently, locating a boring near the quarry would have the added benefit of providing data on the subsurface stratigraphy and elevation of basement rocks in this poorly characterized area.

No Quaternary-active faults were confidently identified within the naval magazine, and the area is not as promising a target for drilling as the Quaternary structures in the northern part of the island. Nonetheless, the Talofoto fault zone, a discontinuous series of faults, lineaments, and joint zones having variable expression and no positive evidence of Quaternary activity (Tracey et al., 1964), does trend across the magazine. Without identifying any clearly Quaternary-active fault strands along the Talofoto fault zone, we suggest that the mapped faults passing near the Fena Water Treatment Plant and northwest gate to the naval magazine may be a possible drilling target. Although Seigrist and Reagan (2008) show these faults as buried underneath (and not displacing) the Oligocene Talisay member of the Umatac Formation, these faults may have zones of increased porosity at depth. A less accessible alternative are the group L lineaments. The discontinuous lineaments of group L do have a similar northwest to north-northwest trend to the overall structural trend of the major faults on the island, and in the absence of widespread Quaternary-age deposits in the area that clearly indicate their level of activity, these features may warrant additional investigation through drilling.

During our visit to Guam, we learned of, but were unable to obtain and review, seismic data collected for the Northern Guam Lens Aquifer study (CDM, 1982). We recommend these data be reviewed prior to the final selection of drilling locations because these subsurface data may provide important insights into the fault architecture at depth. Furthermore, we recommend review of any available site-specific subsurface data on the elevation of the limestone-volcanic basement contact, potential fault dips, drilling capability of the available equipment, and the depths of overlying local aquifers prior to the final selection of drilling location as subtle changes in these variables may greatly influence the success of reaching the targeted fault zone.

SUMMARY

This study organized and evaluated geologic data from Guam for the presence or absence of Quaternary faulting in support of a multidisciplinary evaluation of the geothermal potential on the island. Evidence for faulting within Pleistocene limestone units in northern Guam includes distinct topographic escarpments visible in detailed LiDAR-derived DEMs that are locally coincident with mapped brecciated zones and continuous for up to approximately 12-15 kilometers. Exposures within recent excavations and quarries show discrete faults with damage zones on the order of tens of centimeters in width, as well as broader, meter-scale zones of complex fracturing cut by through-going faults. Well and drill core data shows that faults in the basement rocks may be controlling deformation of the overlying limestone deposits. In southern Guam, evidence for faulting within Oligocene- to Pliocene-age volcanic, volcanoclastic, and limestone deposits exists but currently available data cannot conclusively demonstrate that the faulting occurred during the Quaternary. Further investigation into the nature of the Talofoto fault zone may uncover evidence of Quaternary activity that is not apparent in data evaluated for this study. The lineaments between Ritidian Point and Mount Santa Rosa, the Tamuning-Yigo fault zone, and the Adelup-Pago Point fault zones are the best expressed structures on the island worthy of further investigation.

Most of the data reviewed for this study indicate a low likelihood for a commercial-grade geothermal resource on Guam. Topographic escarpments and zones of faulting on Guam may be related to tectonic processes driven by the nearby Mariana subduction zone, crustal-scale gravitational collapse (i.e. island-scale landslides), or a combination of both processes.

However, to fully address the potential for geothermal power sources on Guam, limited exploration of the subsurface via targeted drilling should be considered. The locations with the most potential include fault A1 on Anderson AFB, the Tammuning-Yigo fault zone, the Perez brothers' quarry near the Hilton hotel in Tumon, and possibly sites within the naval magazine.

REFERENCES

- Camp Dresser & McKee Inc. (CDM), 1982, Northern Guam lens study, Groundwater management program, Aquifer yield report prepared for the Government of Guam, Guam Environmental Protection agency, variously paged.
- Dames and Moore, 1994, Earthquake Hazard Vulnerability Study: Guam, Mariana Islands, unpublished consultants report submitted to the Civil Defense/Emergency Services Office, Government of Guam, December 1994.
- Dickinson, W.R., 2000, Hydro-Isostatic and Tectonic Influences on Emergent Holocene Paleoshorlines in the Mariana Islands, Western Pacific Ocean, *Journal of Coastal Research*, vol. 16, no. 3. pp. 735-746.
- Fryer, P., 1996, Evolution of the Mariana Convergent Plate Margin System, *Reviews of Geophysics*, Vol. 34, no. 1, p. 89-125.
- Fryer, P., Wheat, C.G., Mottl, M.J., 2009, Mariana Blueschist Mud Volcanism: Implications for Conditions with the Subduction Zone, *Geology*, v. 27, no. 2, p. 103-106.
- Heeszel, D.S., Wiens, D.A., Shore, P.J., Shiobara, H., and Sugioka, H., 2008, Earthquake evidence for along-arc extension in the Mariana Islands: Geochemistry, Geophysics, Geosystems (G³), v. 9, no.12, doi: 10.1029/2008GC002186.
- Holcomb, R.T., and Searle, R.C., 1991, Large Landslides from Oceanic Volcanoes, *Marine Geotechnology*, Vol. 10, pp. 19-32.
- Innovative Technical Solutions, Inc., (ITSI) 2005, Kinematic and Dynamic Studies: Genetic Occurrence Models for Geothermal Prospecting: report submitted to the U.S. Navy Geothermal Program Office, contracts N68936-04-C-0057 and N68936-04-C-0054, 82 p.
- Jenson, J.W., Keel, T.M., Mylroie, J.R., Mylroie, J.E., Stafford, K.W., Taborosi, D., Wexel, C., 2006, Karst of the Mariana Islands: The Interaction of Tectonics, Glacio-eustasy, and freshwater/seawater Mixing in Island Carbonates, *in* Harmon, R.S., and Wicks, C., eds., *Perspectives on karst geomorphology, hydrogeology, and geochemistry—A tribute volume to Derek C. Ford and William B. White: Geological Society of America Special Paper 404*, p. 129-138.
- Khosrowpanah, S., Heitz, L., Wen, Y., Park, M., 2007, Developing a GIS-based potential model of the Ugum Watershed, WERI Technical Report No. 117, 95 p.

- Kilmer, F.K., Resig, J.M., Longshore, J.D., 2003, A stratigraphic study of Late Middle Eocene/Early Oligocene volcanic arc rocks of southern Guam, South Pacific Applied Geoscience Commission (SOPAC) Technical Report 353, May 2003, 54 p.
- Mitchell, N.C., 2003, Susceptibility of mid-ocean ridge volcanic islands and seamounts to large scale landsliding, *Journal of Geophysical Research*, Vol. 108, No.B8.
- Oehler, J., van Wyke de Vries, B., and Labazuy, P., 2005, Landslides and Spreading of Oceanic Hot-spot and Arc Shield Volcanoes on Low Strength Layers (LSL): an analogue modelling approach, *Journal of Volcanology and Geothermal Research*, Vol. 144, pp. 169-189.
- Perez, J., Personal Communication, June 6, 2011.
- Randall, D., Personal Communication, June 7, 2011.
- Reagan, M.K., and Meijer, A., 1984, Geology and geochemistry of early arc-volcanic rocks from Guam: *Geological Society of America Bulletin*, v. 95, p. 701-713.
- Scheman N., 2002, Identification of Erosion Process and Sources of Exposed Patches in the La Sa Fua Watershed of Southern Guam. M.S. Thesis, WERI, University of Guam
- Siegrist, H.G., Lewis, R.R., Jocson, J.M., 1998, Seismic Hazard Vulnerability on Guam—A Summary, WERI Technical Report no. 77, 56 P.
- Siegrist, H.G., and Reagan, M.K., 2008, Geologic Map and Sections of Guam, Mariana Islands, Guam Hydrologic Survey Program, 1:50,000 scale, 1 sheet.
- Tracey, J.I., Shlanger, S.O., Stark, J.T., Doan, D.B., and May, H.G., 1964, General Geology of Guam: U.S. Geological Survey Professional Paper 403-A, 104 P., 3 plates.
- Walker, J.D., Sabin, A.E., Unruh, J.R., Combs, J. and Monastero, F.C., 2005, Development of genetic occurrence models for geothermal prospecting: *Geothermal Resources Council Transactions*, v. 29, p. 309-313.
- Young, F.J., and Nakamura, S., 1988, Soil Survey of Territory of Guam, U.S. Department of Agriculture Soil Conservation Service.

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